# 3D Interferometric Integrated Structure
# For All-Optical Wavelet Transform

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*Abstract*—**In this paper, we present the design of a 3Dinterferometric structure based on a planar waveguides network, able to optically perform the wavelet decomposition of two dimensional input data, such as image pixels.**

**The possibility to implement a system that could offer potential in terms of integrability and robustness is explored. This idea is supported by the existence of methods and optical architectures, based on interferometric structures, for the implementation of the optical wavelet transform. They enable parallel processing on one dimension of the input data and they can be enhanced with the development of structures able to parallelize the processing on two dimensional data.**

*Index Terms*— **optical image processing, optical wavelet transform, 3D interferometric structures, integrated data processing.**

## I. NTRODUCTION

IN recent years, many fundamental developments have been made in the area of optical signal processing. When large data amount has to be processed and/or stored and high speed is required, the information contained in the images, for example, need to be compressed, [1], by removing the least significant elements, e.g. extracting only the visible ones. Thus, the total size of data is reduced substantially, resulting in lower processing and transmission time, and lower storage memory, better use of the transmission media. The non-stationary feature of involved signals, related to the nature of the image signals and the mechanisms of human vision, must be taken into account. Signals with space (or time)-varying spectra can be transformed considering the non-stationary hypothesis. In this case, image signals can accurately represented jointly in space and frequency domains.

Optical Fourier Transform (FT) and optical Wavelet transform (WT) are commonly used and very effective tools [2]. They can be obtained at the speed of light and there are already many research productions and successful application examples [3], [4].

In general, the WT overcomes the Fourier approach limitation in representing non-stationary signals, since the local spectral decomposition can be performed. It allows analyzing the incoming signal at different scales or resolutions.

This powerful tool is supported by different technologies, in fact another approach is the free space image processing [3], [5], whose basic scheme is the one called 4f setup and depending on the specific processing

to implement it exploits the spectral filtering and data manipulation through holograms and phase masks.

The availability of passive technologies, with low loss and dispersion, such as network of single mode fibers or planar lightwave circuits [6], [7] for the implementation of optical transforms, suggests the possibility to design optical integrated architecture for image data processing.

These approaches are explored with the aim to perform the parallel processing of the two dimensions of the image input data with the support of recent development of 3D structures and material optimization as well, such as planar waveguides layered structure or direct 3D writings on materials such as sol-gel or glass through femtosecond laser [8], showing potential on the implementation of three dimensional integrated interferometry.

The possibility to exploit integrated 3D structures for optical compression is considered in the framework of the project CITO – Optical Transform for Image Compression.

In this paper, we demonstrate, through simulative approach, the implementation of the two level wavelet transform of image data, exploiting an interferometric structure based on a planar waveguide network, which will enable the implementation of a 3D integrated passive scheme for all optical DWT.

## II. 3D SCHEME FOR 2D OPTICAL DISCRETE WAVELET TRANSFORM

A schematic of a functional architecture for all-optical image acquisition, processing and transmitting is presented in Fig.1. This approach allows handling images maintaining all functionalities in the optical domain, with the first relevant achievement of overcoming the OEO bottleneck.



Fig.1 All-Optical System building blocks

We focus on the two central functionalities: signal decomposition through Optical Wavelet Transform, OWT, and compression (Thresholding).

Our approach for implementing the data decomposition (reconstruction) is based on the Discrete Wavelet Transform (DWT). After data transform, the thresholding is performed in order to select only the portions of interest from the signal decomposition, which can be implemented

through Photonic Analog-to-Digital Converter or Non Linear devices (e.g. nonlinear crystals) and uses specific selection criteria related to the final applications.

DWT can be evaluated via recursively filtering the signal by halfbandlowpass$H[n] = \sum_{k=-\infty}^{\infty} x[k]\, g[2n-k]$and highpass$G[n] = \sum_{k=-\infty}^{\infty} x[k]\, h[2n-k]$ filters, which include subsampling of factor 2 following the Mallat pyramidal decomposition algorithm, [9].

The low-pass and high-pass filters associated with theHaar wavelet can be implemented through 3 dB asymmetric couplers [10], as shown in the next schematic of Fig. 2a), giving as outputs the scaling ($c_{ij}$) and detail ($d_{ij}$) coefficients of the input signal.

In order to implement the optical wavelet transform of a set of input data, a 3 dB asymmetric couplers network can be designed as in Fig. 2b); in this case the wavelet coefficients are computed up to the M=3 level.



$a_0$      $b_0 = \sqrt{1/2}(a_0 + a_1)$

$a_1$      $b_1 = \sqrt{1/2}(a_0 - a_1)$

$$S = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$
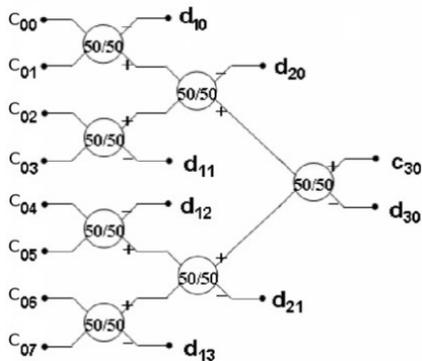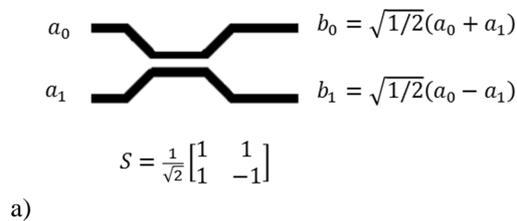
a)



b)

Figure 2 a) 3 dB asymmetric coupler scattering matrix; b) Optical 3 dB asymmetric coupler network for DWT evaluation.

For image and higher dimensional signal processing, this network can be properly designed in order to obtain a 3D integrated passive structure for the parallel data processing of image data as instance.

In principle, this planar structure can be stacked in order to create a 3D interferometry device which is able to receive a set of input fields distributed all over a 2D pattern (e.g. pixelated image), (Fig. 3).

In this case the data decomposition has to be implemented by properly coupling along the two spatial coordinates, one dimension at time (i.e. horizontally, vertically), allowing the parallel processing of the 2D coefficients.
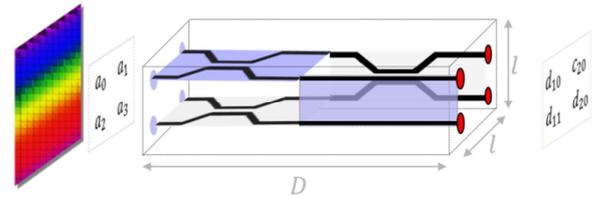


Fig.3 3D basic module for optical parallel 2 levels DWT of 2x2 data matrix.

III. MAGIC-T DESIGN

The asymmetric coupler design is based on Couple Mode Theory (CMT) and the work presented in [10-12]. Visible spectrum couplers must be obtained for specific bands centered on 532 (Red), 635 (Green), and 405 nm (Blue).

Two non-identical waveguides are designedwith the requirements to have a maximum coupling of 50% and the output waves have to be:

- in phase (sum) with the input for wider waveguide
- 180º phase difference (subtraction) for the narrower waveguide input.

We refer to this condition as pi@3dB; such a device is called 'magic-t' and its structure is depicted in Fig. 4.
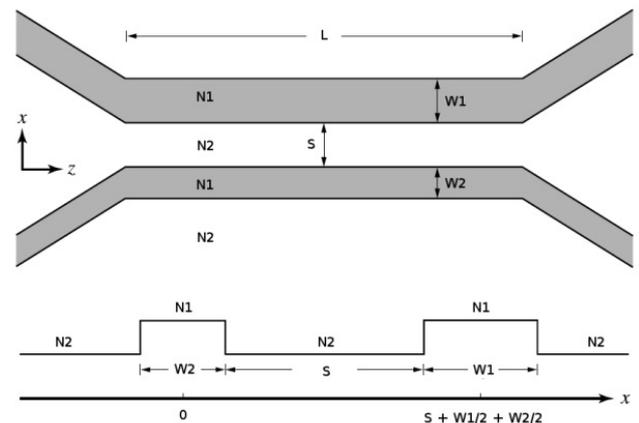


Figure 4 Geometry of Asymmetric Coupler and Parameters for its Optimization for 'Magic-T' design.

CMT states that one can obtain such a coupler by properly setting the parameters:

- $\Delta N$, (N1, N2) – Refractive Index Contrast: contrast is defined by the materials technology used to fabricate the device. The larger the contrast, the stronger is the confinement of light to the waveguide, resulting in less coupling, Current technology preferences are Silica (Si/SiO2), CMOS, Polymer and Sol-Gel. Moreover, material choice influences the overall size of waveguides for single mode propagation.
- S – Separation between waveguides: this parameter is fundamental to control the coupling strength. More separation means less coupling.
- W1, W2 – Waveguides Widths: difference between widths controls the phase difference between coupled modes, and thus, the length corresponding to the 180º phase difference between output waves.

- L – Couplers Length: the two waves propagate at different speeds in each waveguide, therefore, at different lengths the phase difference between waveguides will change.

CMT gives us the equations to achieve the desired functionality [12] although obtaining their solutions demands a considerable complexity. Instead of solving the equations to obtain the coupling coefficient plus the two propagation constants, we used a method to optimize the parameters for the

pi@3dB by using Beam Propagation Method software.

First step is material choice based on available technology, defining the ΔN value, usually chosen as less than 2%. Secondly, we found the maximum width of the waveguide that supports single mode propagation. W1 is set lower (at least slightly for error tolerance in fabrication) than the cut-off width for second mode. W2 is set equal to W1 and a length L is chosen sufficiently large to observe at least a complete coupling of energy from one waveguide to the other. On the third step, the system is repeatedly simulated, placing a source only at waveguide 2. Separation S is set to 0 and increased whereas W2 is decreased. The balance between both parameters is reached when exact 50% coupling is observed, that is only half of the energy passes from one waveguide to the other. For last, the couplers length coincides with the maximum coupling, where a 180º phase difference between waves in waveguide 1 and 2. That will be the coupler's length L. However, asymmetry can also be modeled by setting different values of refractive index for both waveguides and this would also provoke different propagation constants.

## IV. SIMULATIONS RESULTS

Simulations of this device were performed using OptiBPM software. A first coupler was designed for Silica using parameters N1 = 1.50, N2 = 1.49. This design included the transition s-bend of the coupler, which guided light into the coupling region. S, W1, W2 and L were found to be 1.8, 1.8, 1.75 and 346 (all in um) respectively. The separation between "pixels" (transition arms input) is 8.5 um and its length is 200 um.

The used wavelength is 0.635 um (visible Red).The basic moduleoperation was simulated considering the planar equivalent circuit. The results can be seen on Fig.5, for amplitude and phase.On the top view, coupler 1 is fed by a normalized input on the wider waveguide. Coupler 2 is fed similarly, but on the smaller waveguide. At the end of stage one, it can be observed that both coupler outputs at both arms are the 50% of the input power, with 0º phase difference for

coupler 1 and 180º for coupler 2, performing the mathematical operation indicated in Fig. 2 a). For coupler 3, at the second stage, for equal input for both waveguides, the sum and difference operations are performed. Using random values for the power intensities at the four inputs (pixels) we have found a maximum deviation of 10% from the theoretical predictions for the wavelet coefficients, and a mean deviation of 3%, both values measured per pixel. These results were obtained carrying out ten DWT simulations, (i.e. 40 pixels),we consider this statistical behavior as an indicator.
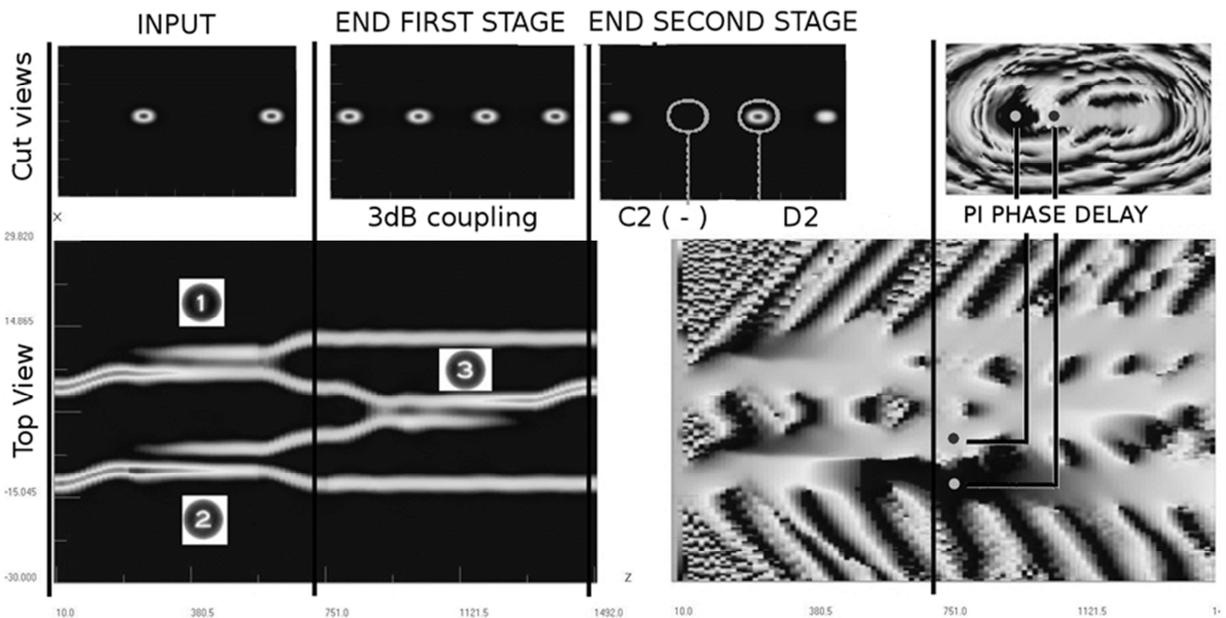


Figure 5 Simulation resuts for optical "magic-t" Haar wavelet transform typical test.

## V. CONCLUSION

The implementation of the two level wavelet transform of image data, exploiting an interferometric structure based on a planar waveguide network was presented. Simulation results show good indicators for achievement of the optical wavelet transform operation performed by "magic-t" couplers network.

## ACKNOWLEDGMENT

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